



A Review on Nanobots in Pharmaceutical Sciences: Pioneering the Future of Precision Medicine and Smart Therapeutics

Prathyusha Vuddanda*

Asst. Professor, Dept. of Pharmaceutics, Narayana Pharmacy College, Nellore. India.

Received: 25 January 2026

Revised: 10 February 2026

Accepted: 26 February 2026

ABSTRACT:

The convergence of nanotechnology, artificial intelligence, and biomedical engineering has introduced a transformative paradigm in pharmaceutical sciences, positioning nanobots as a promising frontier in next-generation therapeutics. Nanobots are engineered nanoscale devices capable of autonomous or semi-autonomous functions, offering unprecedented opportunities in drug discovery, targeted drug delivery, diagnostics, and personalized medicine. Unlike conventional nanocarriers, nanobots can sense, navigate, and respond dynamically to specific biological microenvironments, enabling highly precise therapeutic interventions. Recent advancements highlight the feasibility of nanobots for site-specific drug delivery in oncology, cardiovascular diseases, neurodegenerative disorders, and infectious conditions. Through molecular recognition, magnetic guidance, and stimulus-responsive mechanisms, nanobots can overcome physiological barriers such as the blood-brain barrier, reduce off-target toxicity, and enhance therapeutic efficacy. In diagnostics, nanobots enable real-time disease monitoring, early molecular-level detection, and integration with biosensing platforms for feedback-controlled therapy. The future of nanobots in pharmaceutical applications is strongly linked with artificial intelligence and machine learning, facilitating intelligent navigation, adaptive decision-making, and patient-specific precision dosing. Additionally, their potential extends to regenerative medicine, minimally invasive interventions, and intracellular gene and protein modulation. Despite these advancements, challenges related to biocompatibility, scalable manufacturing, regulatory approval, ethical considerations, and long-term safety remain. Addressing these barriers is crucial for successful clinical translation and global adoption of nanobot-enabled smart therapeutics.

Keywords: Nanobots, Targeted Drug Delivery, Precision Medicine, Artificial Intelligence in Pharma, Smart Therapeutics

INTRODUCTION

The field of pharmaceutical sciences has gone through an unprecedented radical paradigm shift owing to a synergism between nanotechnology, artificial intelligence, robotics, and biomedical engineering¹⁻⁵. This multidisciplinary approach has helped to considerably empower the development of vastly sophisticated drug delivery systems to address the complex and multifactorial characteristics inherent in human diseases^{18,22}. The conventional drug delivery systems, though clinically established, often face major limitations in biodistribution, systemic toxicity, penetration, pharmacokinetics, drug release characteristics, etc^{4,27,30}. These have often led to diminished efficacy, toxicity, and variable patient outcomes due to relatively suboptimal drug action³⁴.

Precision medicine has thus generated the imperative to develop therapeutic platforms that transcend the traditional “one-size-fits-all” approach^{18,22}. In point of fact, modern-day healthcare strategies demand activating interventions which are site-specific, stimulus-responsive, and patient-specific, and can flexibly modify behavior within an individual’s microenvironment^{15,17}. Such a characteristic is to be noted, particularly in the management of diseases like cancer, neurodegenerative diseases, cardiovascular diseases, and chronic infections, where effective management necessitates overcoming huge heterogeneity challenges at molecular, cellular, and tissue levels^{16,25}.

In this changing dynamic system of nanoworlds, the current status of nanobots or more specifically nanorobots and nanomachines has evolved as a revolutionary form of nanotechnology that is within the range of 1-1000 nm with the dimension of self-sustained or semi-autonomous situational operations live inside the bodies of the subjects^{6,9}. Unlike classical nanocarriers that include liposomes, polymers, and micelles, which are capable of diffusing passively or through specific ligand-mediated targeting properties, the significant feature of nanobots is that they are capable of navigating their environments actively^{3,15}. The feature has accordingly redesignated the status of classical intelligent drugs.



One of the distinguishing features of nanobots is the capacity to engage with the live environment with the aid of integrated sensing parts that are equipped to identify biological signals such as the presence of pH changes, enzymes, and cell surface proteins^{13,24}. This helps the nanobots to specifically target specific tissues while causing minimal harm to non-diseased cells¹⁷. The available propulsion methods such as magnetic control, use of enzymes as propulsion systems, and sound/light-based propulsion allow the nanobots to bypass biological barriers such as dense matrices, the vasculature within tumors, and the blood-brain barrier^{8,10,11}.

Recent advances in DNA origami, magnetic nanomaterials, biohybrid technologies, and artificial intelligence have accelerated the translation of nanobots into practical biomedical applications^{1,2,12,14, 21}. DNA origami allows programmable nanoscale construction with a high payload capacity and controlled release capabilities^{12, 13}. Magnetic nanomaterials provide a means of externally guided localization and navigation assisted by imaging techniques^{10, 11}. In addition, biohybrid systems improve biocompatibility and functional performance in a biological environment^{8, 19}. Moreover, artificial intelligence provides navigation, decision-making, and optimization in therapy based on patient specific data^{21, 22}.

These technological advancements have extended the application scope of nanobots in drug delivery, disease detection, theranostics, gene therapy, regenerative medicine, and minimally invasive interventions^{9,18,23,26}. Put together, these works position nanobots in the vanguard of the oncoming revolution in precision medicine and smart therapeutics, transforming pharmaceutical sciences from systems of reactive drug delivery into proactive personalized healthcare platforms^{18, 22, 34}.

Evolution Of Nanobots In Pharmaceutical Sciences

The intellectual roots of the concept of the design of nanobots originated with the visionary ideas of a renowned physicist, Richard P. Feynman, who in his lecture on the theme “There’s Plenty of Room at the Bottom” in 1959 suggested the idea of the manipulation of matter on the atomic and molecular levels². This lecture could be considered one of the main intellectual precursors of the concept of nanotechnology, though the latter term was not yet coined⁶. Feynman’s ideas on the manipulation of matter went beyond miniaturization trends and could be especially applied to life sciences due to their unique nanoscale biological processes². Proteins, DNA, enzymes, and cellular organelles are natural nanomachines, and it was a recognition of this fact that led to studies of man-made nanodevices that could perform similar tasks to natural ones^{9,27}. Although the technology was not available at the time, Feynman’s idea drove nanoscience studies for decades².

The bridge between theoretical concepts and practical reality was achieved with the advent of nanofabrication and characterization techniques such as scanning tunneling microscopy and atomic force microscopy that enabled the direct imaging and manipulation of nanostructures with unprecedented accuracy^{6,33}. The parallel advances made in lithography, self-assembly techniques, and synthetic chemistry paved the way towards the development of nanostructured materials applicable to biomedical fields⁶. The expanding fields of molecular biology and biochemistry continued to expose the highly ordered nanoscale structure of living matter, including the structure of DNA, protein folding, enzyme reactions, and transport mechanisms within the cell^{9,27}. This led to the development of nanodevices that could work seamlessly with living matter, producing early nanomedicine approaches such as drug-carried nanoparticles, nanosensors, and drug delivery systems^{4,15}. The term “nanorobot” was then proposed to denote programmable nanobots for the performance of biomedical operations⁹. Theoretical models derived from such concepts initially envisaged autonomously operating nanobots that would move to different areas within the body to diagnose and treat diseases^{6,9}. Although far-fetched initially, such ideas led to international collaboration among physicists, chemists, engineers, biologists, and pharmacists¹¹. By the late 1990s and early 2000s, the convergence of nanotechnology and pharmaceutical sciences resulted in the development of the first generation of functional nanodevices, including liposomes, polymeric nanoparticles, dendrimers, and inorganic nanocarriers^{4,15}. While these systems were not fully autonomous, they demonstrated the feasibility of nanoscale drug delivery and highlighted the limitations of passive targeting strategies^{16,17}. Subsequent advances in modeling, computing, robotic engineering, and artificial intelligence have made the integration of sensory components, actuators, feedback mechanisms, and control systems feasible at the nanoscale, giving birth to semi-autonomous and autonomous nanobot technologies^{9,21}. These advances represent a metamorphosis from futuristic concepts to pragmatic pharmaceutical tools that have the potential to revolutionize intelligent drug therapy^{18, 33}.

Structure And Design Of Pharmaceutical Nanobots

Core Components of Nanobots

At the functional level, the performance of a pharmaceutical nanobot is enabled by the precise integration of various nanoscale components, each suited for a particular purpose^{1,6}. These nanocomponents, which work in perfect synergy, facilitate the autonomous navigation, sensory analysis of the environment, intelligent decision-making, and therapeutic response within complex biological systems^{9,11}. The Schematic representation of a pharmaceutical nanobot given in the below figure 1. This integrated framework represents the physical skeleton of the nanobot while providing mechanical stability, biocompatibility, and functionalities for integration^{18,3}.

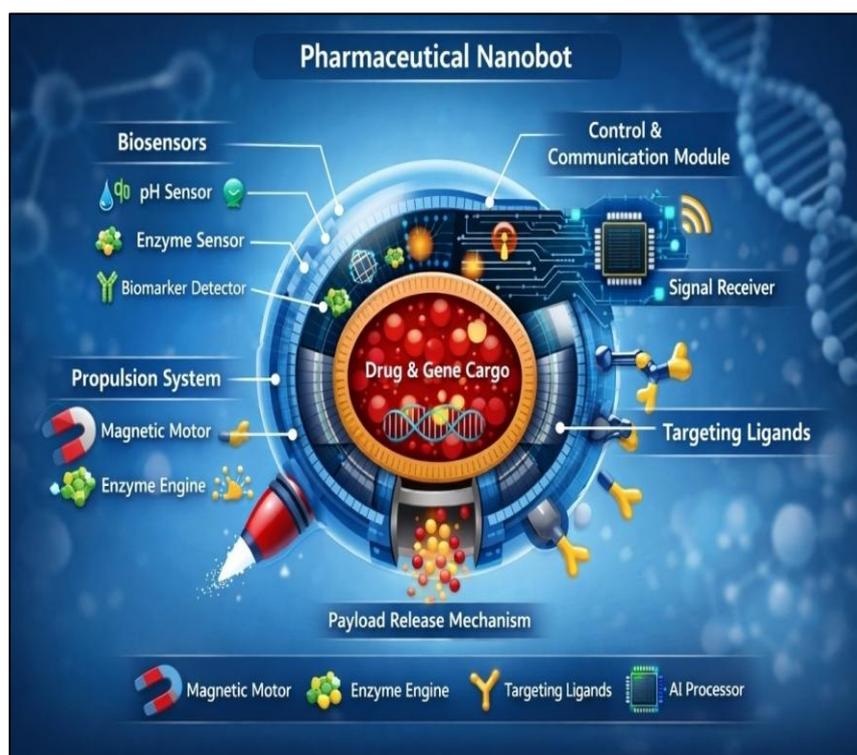


Fig.1:Schematic representation of a pharmaceutical nanobot

DNA Origami–Based Frameworks

DNA origami is an advanced technique in the field of nanotechnology that utilizes the inherent properties of DNA as a tool for the creation of "nucleating molecules." DNA origami is based on the idea of "nucleating molecules," and it utilizes the properties of DNA to create accurate structures. The technique involves the folding of DNA molecules into precise shapes by allowing hundreds of synthetic oligonucleotides, known as staple strands, to bind to a stretched bacteriophage M13 DNA molecule^{12,13}. These staple strands have the properties of Watson-Crick complementarity.

Atomic-Level Precision: Structural Control

The greatest advantage of DNA origami is its atomic precision as well as the spatial resolution of approximately 1–2 nm^{12,14}. This allows the precise placement of the drug as well as the siRNA as part of the payload with precision for ensuring optimal therapeutic impact¹³. Similarly, the technique enables the precise orientation of the ligands such as aptamers as well as peptides^{13,14} for optimal binding results. The schematic representation of Atomic-Level Precision and Structural Control is given in figure 2. This is essential when it comes to the biomedical nanobots as the precision of the position is what makes a big difference³¹.

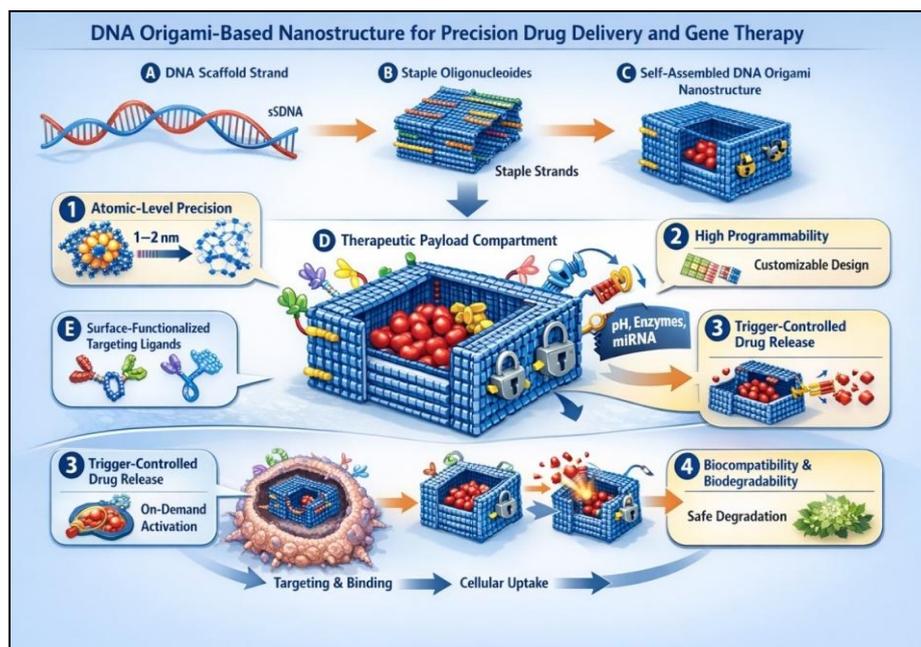


Fig.2:Schematic Representation Of Atomic-Level Precision And Structural Control

High Programmability and Structural Versatility

DNA origami has the flexibility to allow for the programming of structural properties such as the size and function of the origami structure using special computer software such as caDNA¹². Various shapes of structures such as boxes, cages, barrels, capsules, tubular carriers, rod shapes, hinges, molecular locks, logic switches, etc., can be programmed using the above software. The structural versatility of DNA origami-based platforms allows the integration of sensing, targeting, and therapeutic functions into a single nanoscale system¹³. The schematic representation of polymer based nano structure scaffold architecture in figure 3. Additionally, various payloads can be transported at the same time, facilitating combination therapy modalities such as chemotherapy combined with gene therapy^{12, 26}.

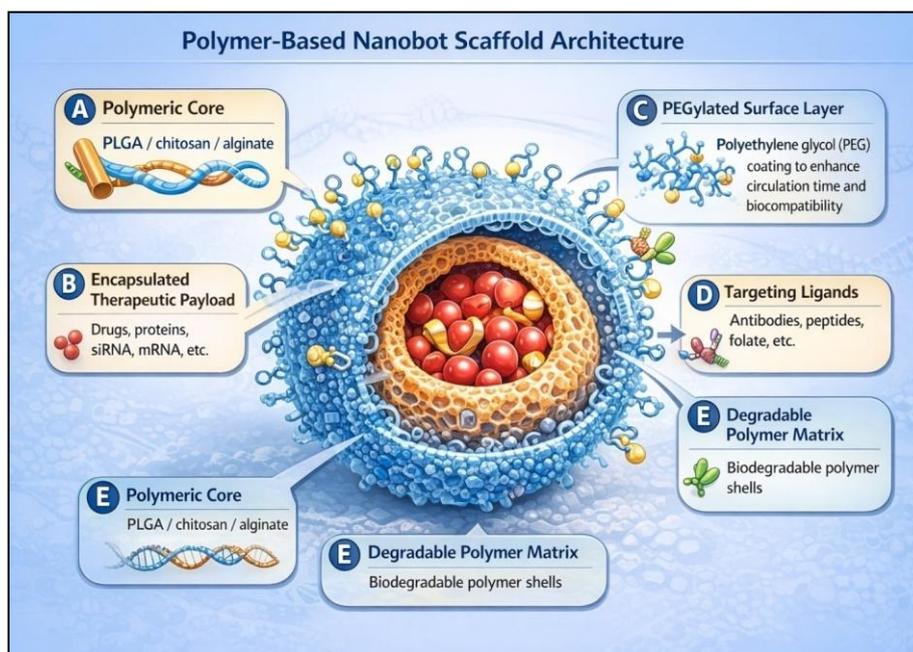


Fig.3:Schematic Representation Of Polymer Based Nano Structure Scaffold Architecture

Stimuli-Responsive Behavior

DNA origami nanostructures can be designed to sense specific kinds of molecular and environmental stimuli and change conformation accordingly^{13,24}. These stimuli can arise from particular pH levels associated with tumors, disease-related enzymes, certain types of nucleic acids including miRNA and mRNA, as well as small molecules like ATP, cytokines, and tumor markers^{13,24}. This allows nanobots to remain stable under physiological conditions while targeting disease more accurately upon activation^{17,25}.

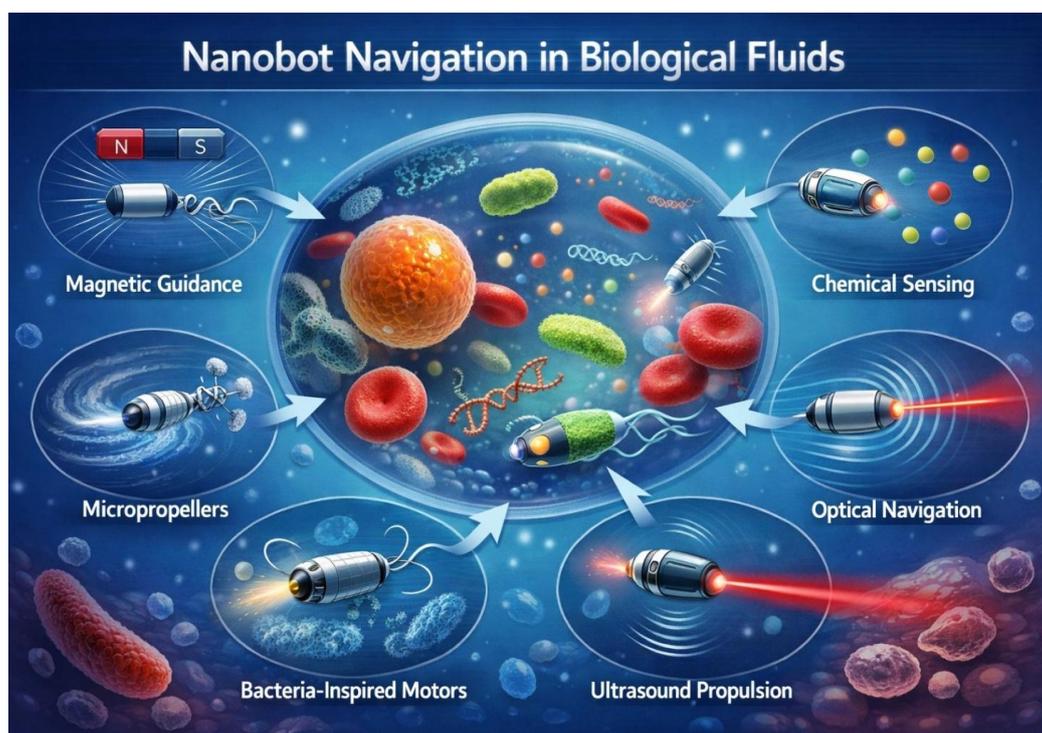


Fig.4:Nanobot Navigation In Biological Fluids

Applications in Smart drug delivery

The various advantages of using frameworks based on DNA origami technology include: therapeutic drugs encapsulated in a protective framework of DNA are protected from premature degradation. Secondly, the framework that facilitates target cell recognition is important. Finally, drug release is controlled by specific signals of intracellular signals; thus, drugs do not accumulate systemically. The nanobot navigation in biological fluids is given in figure 4. DNA origami frameworks: drug delivery has been studied using DNA carriers. Doxorubicin is one of the most commonly studied drugs. In addition, nucleic acid drugs including siRNA and antisense nucleic acid drugs have been shown to be delivered using these frameworks.

Role in Gene Therapy and Nucleic Acid Delivery

In particular, DNA origami has been recognized for its potential in gene therapy owing to its intrinsic compatibility with nucleic acids^{12,26}. Such strategies are capable of delivering plasmid DNA, siRNA, miRNA, as well as components for genome editing with CRISPR-Cas systems, together with a protective effect from enzymatic degradation^{13,2}. Furthermore, DNA-based nanobots could be designed to have specific trafficking patterns within the cell membrane, as well as within the nucleus. This would provide the accuracy needed to regulate genes correctly and allow adaptive responses to changes in intracellular patterns of gene expression^{13,2}.

Biocompatibility and Biode

DNA nanostructures possess inherent biocompatibility due to their biological origins¹². DNA nanostructures designed properly have low immunogenic potential, degrade by enzymes, and release harmless products as well as no inorganic residuals^{12,28}. The biodegradability of this DNA origami reduces long-term toxicity risks compared to metal-based and polymer-based nanoparticles. In sophisticated pharmaceutical nanobots, DNA origami is capable of being used as structural backbones, smart cargo containers,



molecular logic circuits, and communication interfaces with bio-signals¹³. DNA origami, when integrated with sensors, propulsion systems, and external control systems, enables the construction of self-regulated smart nanotherapeutic systems^{13,21}.

Polymer-Based Scaffold

In terms of structural platforms for pharmaceutical nanobots and nanocarriers, polymeric scaffolds are perhaps the most investigated option with considerable translatability potential^{4,15}. Notably, scaffolds are prepared using biodegradable and biocompatible polymers, which provide considerable scope for controlling the mechanical properties, degradability, and release characteristics of the polymers^{15,24}. As such, a polymeric scaffold is perhaps an essential feature associated with modern nanomedicine^{4,27}.

Types of Polymers Used for Constructing the Nanobot Structure

Poly(lactic-co-glycolic acid)

PLGA is an FDA-approved, biodegradable copolymer formed by lactic acid and glycolic acid monomers in the United States^{27,30}. After hydrolysis, it degrades back into lactic and glycolic acid and easily leaves the body as part of natural metabolism pathways^{15,27}. The rate at which PLGA is degraded can be controlled by adjusting the ratio of lactic acid to glycolic acid to create a customized drug release profile¹⁵. PLGA material has a good encapsulation efficiency for hydrophobic, as well as hydrophilic, compounds. It can be used to control the delivery of chemotherapeutic agents, vaccines, and depot formulations^{4,15}.

Polyethylene Glycol (PEG)

Polyethylene glycol, being a hydrophilic molecule, is often employed to modify nanobots through a surface modification approach termed PEGylation¹⁵. The ability to form a hydration shell around the nanobots with PEGylation effectively reduces the adsorption of proteins, thereby avoiding opsonization and recognition by the immune system^{15,17}, thereby increasing the systemic circulation time and allowing the nanobots to accumulate in the tumor using the enhanced permeability and retention effect¹.

Natural Polymers: Chitosan and Alginate

A positively charged chitosan is prepared from chitin. It shows properties of mucoadhesive character, increased membrane permeability, and has the highest affinity towards nucleic acids^{15,26}. It is best used in the field of gene delivery and mucoadhesive drug delivery²⁶.

Alginate is known to be an anionic polysaccharide. Gelation of the material is achieved with the help of divalent ions such as calcium. This facilitates the mild method of formulation that is viable for protein/cell viability. Alginate is capable of pH-sensitive drug release. It is commercially used for oral, mucosal, trans-gene applications^{24,26}.

Mechanical & Structural Advantages

Polymer-based nanobots possess the advantage of being developed with tunable mechanical properties that can protect against various physiological stresses such as the shear stress of blood circulation, cellular uptake stress, and endosome stress²⁵. The mechanical strength of the nanobots is easily achieved through the regulation of the molecular weight of the polymers and the blending of different polymers to produce a range of structures from soft to hard¹⁶.

Controlled Degradation and Drug Release

The feature of polymeric matrices is the controlled degradation pattern they exhibit¹⁵. Along with drug release mechanisms such as diffusion-controlled drug release and polymer erosion-controlled drug release, the processes have the opportunity to be controlled and influenced through environmental factors such as pH and enzymatic activity^{15,24}. These mechanisms deliver sustained drug release, which generally lasts from several days to several weeks, and the dosing frequency and systemic toxicity are minimized^{15,27}. Surface functionalization techniques such as PEGylation and ligand conjugation can improve circulation time, immune evasion, targeted delivery, and cellular traversal^{15,17}.

Versatility in Encapsulation and Theranostic Capability

The polymeric nanobots can load a wide range of theranostic and diagnostic payloads, including small-molecule drugs, proteins, DNA, siRNA, mRNA, and imaging contrast agents such as fluorescent dyes and MRI probes^{4,23}. This enables a combination therapy and/or theranostic applications within a single nanobot platform²³. Due to the availability of FDA-approved polymers, scalable



manufacturing techniques such as nanoprecipitation and emulsion methods, and reproducible batch-to-batch production^{4,27,30}, polymer-based nanobots are highly favored for clinical translation. These attributes thus facilitate their translation from bench to bedside²⁷.

Nanomateriales Metalicos E Hibridos

Metallic and hybrid nanomaterials, thanks to their exceptional physical properties, external controllability, and intrinsic imaging capabilities, are one of the highly promising classes of structural platforms for pharmaceutical nanobots^{7,10,11}. Since inorganic metallic or metal oxide cores may be made up of simple gold or iron oxide nanoparticles, they are surface-modified with organic or biological materials in order to enhance biocompatibility and functionality of these nanobots^{7,23}.

Gold Nanomaterial

Gold nanomaterials are one of the most intensively researched metallic nanomaterials due to their high chemical stability, resistance to oxidation, and high surface plasmon resonance, along with ease of functionalization via thiol reactions^{7,10}. These attributes of gold nanostructures make them an ideal candidate for photothermal treatment, targeted medicine and gene delivery, enhancements for computed tomography scans, and in various biosensing approaches^{7,23}. Gold nanomaterials can be synthesized into different forms like nanoparticles, nanorods, nanoshells, and nanocages to tailor optical and therapeutic properties to desired fields of biomedical applications¹⁰.

Iron Oxide Nanoparticles

Iron oxide nanoparticles composed of Fe₃O₄ or γ -Fe₂O₃ display superparamagnetism, a condition which makes them highly sensitive to external magnetic field influences^{1,11}. These nanoparticles are biodegradable to iron ions which are compatible with iron metabolism in the body and display excellent biocompatibility with Magnetic Resonance Imaging techniques^{11,28}. Nanobots based on iron oxide are used in magnetic targeting/navigating applications, hyperthermia treatment, MRI-assisted drug delivery systems, and cell tracking²¹.

Magnetic Responsiveness and Guided Navigation

The benefits of using metallic nanomaterials, especially iron oxide nanosystems, lie in their response to external magnetic stimuli¹⁰. Magnetic field gradient can be used to guide the motion of the nanobots toward a target region, promote maximum accumulation of the nanobots in the diseased region, minimize the accumulation in areas away from the target, and monitor the location of the nanobots in real-time. Such externally guided navigation represents an important characteristic feature of sophisticated precision nanomedicine, facilitating non-invasive control and deep tissue penetration without recourse to any kind of surgical intervention¹¹.

Structural Durability and Mechanical Stability

Compared with organic nanocarriers, the use of metal frameworks has the advantages of stronger strength, rigidity, as well as resistance to degradation^{7,11}. Such stability enables nanobots to be able to withstand shear stress in the body and remain stable through repeated imaging or therapeutic cycles¹¹. In addition, metallic scaffolds enable the integration of complex multifunctional assemblies such as sensors, propulsion systems, and imaging agents, which are vital toward their long-term therapeutic potential^{7,23}.

Imaging Compatibility and Theranostic Capability

The images produced by metallic nanomaterials have suitable imaging contrast that helps in the real-time tracking and diagnosis of the concerned aspect^{7,23}. Iron-based nanomaterials have the capability to produce magnetic resonance images; gold-based nanomaterials can produce computed tomographic images, together with photoacoustic images. Gold-based nanostructures can produce optical images⁷. The unification of the diagnostic and the therapeutic aspects within a single nanobot lays the basis for the development of theranostic nanomedicine²³.

Hybrid Nanomaterials: Inorganic Organic Integration

The hybrid nanomaterials are designed by incorporating an outer shell composed of polymers, lipids, silica, or biological molecules over an inorganic core to leverage the merits of inorganic as well as organic nanosystems^{7,23}. The hybrid nanobot has an inorganic



core, an intermediate shell of polymers or silica, and an outer shell of materials like PEG, PLGA, chitosan, or targeting molecules. Such an integration of the inorganic and organic phases has therefore been established as a "synergistic combination for mechanical stability, biocompatibility, and controlled drug release".

Therapeutic Payload Integration and Biosafety

A hybrid nanobot can be used to carry a wide range of therapeutic payloads, which could be adsorbed onto metallic surfaces as well as encapsulated in polymeric particles^{7,23}. Drug release could be stimulated by specific triggers like pH, temperature, enzymes, and/or external energy^{10,24}. Though metallic nanomaterials possess significant levels of functionality, various surface engineering approaches have been found to be effective in reducing their toxicity levels and circulation times, thereby enhancing their biosafety^{7,28}.

Role in Theranostic Nanobots

Metallic and hybrid nanomaterials constitute the basis of forthcoming theranostic nanobots with capabilities such as targeted delivery, imaging, navigation, and therapeutic activation, as proposed in recent studies²³. This multifunctionality of metallic and hybrid nanomaterials suits the "intelligent, responsive, and personalized" concept of forthcoming nanomedicines.

Propulsion Mechanisms In Pharmaceutical Nanobots

The system used for propulsion itself acts as a unique functional component of pharmaceutical nanobots that helps them to be mobile in the complex medium of fluids such as blood, lymph fluids, mucus, and interstitial spaces^{15,18}. Unlike passive carriers that only reach the targeted place through the bloodstream, the propelled nanobots enhance the efficiency of overcoming physiological barriers and localization of the drug-containing nanobot^{15,25}.

Magnetic Field-Driven Propulsion

Magnetic propulsion is achieved through the integration of magnetic nanoparticles, especially iron oxide particles (Fe_3O_4 or $\gamma\text{-Fe}_2\text{O}_3$), into the nanobot structure^{10,11}. Magnetic nanoparticles respond to an external magnetic field to induce motion in the nanobots¹⁰. This precision placement and control of nanobots by means of magnetic field gradients assure very precise spatial steering/location with high accuracy^{10,11}. Magnetic fields can penetrate deep tissues without any attenuation or reduction, unlike light-based propulsion techniques for navigating nanobots to reach deep-seated organs¹¹. Magnetic propulsion is a vastly researched topic in tumor targeting, drug distribution within the tumor, moving through vascular networks, or treating the liver or pancreas, as examples. Due to its safety, controllability, and imaging capabilities such as MRI, magnetic propulsion stands out as one of the most promising propulsion methods currently available^{10,11}.

Enzyme-P

The enzyme-powered nanobots are capable of harnessing the power from the biocatalytic reactions that result from the conversion of the energy of the chemical substances or the exogenous/endogenous substrates within their environments to enable the nanobots to move. The enzymes immobilized on the nanobot enable the production of the asymmetrical gradients that enable the propulsion of the nanobot. Among the enzymes that have been shown to effectively enable the propulsion of the enzyme-powered nanobots is the enzyme known as the urease. Urease is an enzyme that splits or hydrolyzes the chemical compound known as the urea into ammonia and carbon dioxide. Even though the enzyme-powered nanobots are beneficial for drug delivery and other important applications due to the fact that the enzyme-powered nanobots do not require any energy from the external sources, the enzyme-powered nanobots are proving to offer a potentially useful treatment for the various problems that occur within the different parts of the body. The enzyme nanobots are useful in the transport of drugs to the tumor cells¹⁹.

Light-Responsive Propulsion

In general, photodriven nanobots make use of photothermal or photochemical effects based on gold nanoparticles or photoresponsive polymers^{10,20}. The nanobots use localized heating or photochemical reactions when they are subjected to specific wavelengths of light, like near-infrared radiation¹. "Light-responsive propulsion provides spatio-temporal precision, such that propulsion can be activated 'on-demand' with immediate stop-start motion capability of the nanobot." In addition to that, with the light-responsive propulsion mechanism, the therapeutic intervention is twofold; this is because the propulsion mechanism is combined. Though a number of benefits come along with this approach, there is a limitation with regards to tissue depth penetration, as well as special care having to be taken when choosing the wavelength to prevent damage to tissues in that location²⁰. It is, therefore, only suitable



for treating superficial tumors, for antimicrobial therapy, as well as imaging-guided ablation²⁰.

Comparative Advantages of Propulsion Mechanisms

Active propulsion modes are useful for moving nanobots against the flow of blood, crossing through various biological membranes, targeting the site of diseases with a higher accumulation rate, and lowering the dose of drugs required throughout the system¹⁵. Such characteristics are of primary importance for precision medicine, minimalist therapy, real-time controlled therapy, etc.,^{18,25}.

Sensing Unit And Cargo Chamber Of Pharmaceuteotics

The sensor unit and the cargo compartment have been critical functional entities for pharmaceutical nanobots that facilitate the detection of pathological signals, decision-making, and therapeutic action^{13,18}. The fusion of the sensing and cargo modules has the potential to render nanobots from passive drug-carrying agents to active and wise therapeutic devices that react dynamically to the nanorobot environment^{13,23}. This allows nanobots to identify biochemical and physicochemical markers characteristic of certain diseases, thereby discriminating among pathological microenvironments and healthy tissues^{17,24}.

pH Sensors

pH-sensitive sensing elements can be designed based on pH-sensitive polymers, DNA motifs, and acid-labile linkers that exhibit a response either through changes in their structures or upon exposure to acidic conditions²⁴. These systems are particularly effective in tumor microenvironments, inflamed tissues, and infected sites that exhibit acidosis^{24,25}. pH sensor activation triggers the opening of the cargo chamber, drug release mechanisms, and increased accumulation of the nanobots at the target site of diseases^{24,25}. The offered strategy promises specificity at the target tissues, minimal drug leakage at physiological pH levels, and reduced toxicity in the body^{17,24}. pH sensing has been pertinent in demonstrating its utility in cancer therapy and management of infectious diseases in which an acidic environment is the hallmark²⁴.

Enzyme sensors

Nanobots can be programmed to sense the presence of disease-specific enzymes, such as matrix metalloproteinases within tumor tissues or proteases in the setting of inflammation or degenerative diseases^{13,23}. Enzyme-responsive nanosystems often rely on linker peptides that can be cleaved in the presence of disease biomarkers¹³. This allows for very targeted and specific action, as well as reduced off-target toxicity. It is useful for real-time surveillance and adaptive therapeutic actions. The sensing of enzymes is an essential tool in the overall theranostic nanobot technology¹³.

Redox and Temperature Sensors

Redox-responsive systems can effectively focus on the high oxidative stress condition associated with cancer cells, inflamed tissues, and neurodegenerative disorders^{24,26}. Redox sensors normally contain disulfide bonds. At high ROS conditions, the disulfide bonds are cleaved, thereby releasing the drug²⁴. Temperature-sensitive sensors take advantage of the localized hyperthermia in inflamed or diseased tissues. The temperature-responsive polymers undergo a phase transition at defined temperatures, therefore allowing selective activation and on-demand cargo release at the target site. By integration of redox and thermal sensing, nanobots are superior to detecting subtle physiological variations. This improves therapeutic precision and selectivity radically^{24,25}.

Cargo Compartment: Controlled Encapsulation and Release

The cargo compartment acts as a safe container that carries and releases therapeutic agents upon stimulation by signals from the sensing unit^{13,23}. Controlled encapsulation shelters payloads from inopportune degradation, hence, site-specific drug delivery is guaranteed^{15,24}.

Genetic Materials

In particular, nanobots can be very effective in conveying genetic material and can help overcome critical hurdles in gene therapy programs^{12,26}. Genetic material can be designed to carry siRNA, mRNA, CRISPR-Cas genome editing, and plasmid constructs for stable gene expression^{13,2}. Notably, the cargo chamber shields nucleic acids from degradation by nucleases; it increases uptake as well as escape from endosomes; and it finely tunes intracellular gene regulation^{13,26}. Overall, these features allow for exacting and tailored approaches to cancer therapy, genetic diseases, or infections²⁶.



Proteins and Peptides

The high potency of proteins and peptides makes these compounds attractive therapeutic tools, which are generally susceptible to rapid degradation and poor bioavailability¹⁵. The cargo chamber within the nanobots plays an important role in offering structural protection and increasing the bioavailability of protein and peptide therapeutics^{15,23}.

Ex: enzyme delivery for metabolic disorders, monoclonal antibodies for cancer and autoimmune diseases, and therapeutic peptides for targeted intervention^{15,23}.

Integration of Sensing and Cargo Release

The true therapeutic strength in these pharmaceutical nanobots lies in the tight integration of the sensing and delivery modules^{13,18}. If there are any pathological signals detected, this sensing unit should activate the molecular switches for triggering the release of cargo, making it a closed-loop therapeutic system¹³. This is a closed-loop functionality embodying the very foundation of next-generation nanomedicine, which can enable real-time, adaptive therapy, as well as personalized treatment strategies^{18,21}.

Control and Communication Module

The control and communication module is the intelligence center of the nanobot, and the integration of the sensory inputs along with AI algorithms is made here²¹. Artificial intelligence helps the nanobots to operate independently and make decisions in the environment while optimizing the therapeutic interventions^{21,22}. Machine learning algorithms process the sensor inputs to control the navigation, release kinetics, and therapeutic effects, with communication systems providing an interface through which clinicians could monitor the nanobots, modify the therapy as desired, or stop/withdraw the nanobots as needed^{21,22}.

Navigation And Targeting Mechanisms Of Nanobot

Autonomous Navigation

Nanobots attain their target sites within the biological environment through an autonomous navigation mechanism, including chemotaxis, magnetotaxis, and haptotaxis, by emulating natural cellular locomotion processes^{3,9}. These strategies permit nanobots to dynamically react to the chemical gradient, magnetic field, and tissue-specific adhesion cues present in the biological fluids^{10,11}. Navigation mechanisms by nanobots inspired through biologics enable them to travel with high precision in targeting complex physiological environments, such as blood vessels, interstitial matrices, and tumor microenvironments^{15,25}.

Target Recognition Strategies

Target recognition of pharmaceutical nanobots mainly involves ligand-receptor interactions, which may include antibody-based molecular recognition and peptide/aptamer targeting, and so on^{13,17}. Nanobots bearing disease-specific cellular markers interact selectively with healthy tissues, thereby allowing for targeted delivery of drugs, which spares the health of tissues^{17,2}. This molecular specificity not only increases the effectiveness of therapy but reduces the toxic side effects, an important criterion specifically for precision medicine^{18,25}.

Oncology Applications

Nanobots have tremendous potential in cancer therapy by tackling major challenges like tumor heterogeneity, hypoxia, and drug resistance^{3,9}. The schematic representation of polymer based nano structure scaffold architecture in figure 5. The ability of nanobots to actively target tumor microenvironments helps overcome DEI issues and achieve enhanced drug penetration into tumor tissues^{17,18}. The active targeting and release strategies can enormously minimize systemic toxicity, as seen in conventional chemotherapy^{4,18}.



Fig.5:Schematic Representation Of Nano Mediated Targeted Cancer Therapy

Advantages of Nanobot-Based Targeting

Nanobot-assisted targeting strategies offer a variety of advantages, including early disease detection, continuous health monitoring, and feedback-controlled therapy^{9,18}. These features allow real-time assessment of therapeutic response and enable dynamic adjustment of treatment regimens based on patient-specific biological signals^{21,22}.

Role Of Artificial Intelligence In Nanobot Systems

Artificial Intelligence and Machine Learning enhance nanobot functionality: higher capacities for intelligent navigation, route optimization, avoiding obstacles, and decision-making adaptation. AI-driven systems enable nanobots to respond to a biological change in real time, optimize patient-specific drug dosing, and integrate digital twin models for simulation-based therapy planning.the flow Chart Of AI-Integrated Nanobot-Assisted Precision Medicine Workflow is given in figure 6.Due to this integration, AI transforms nanobots into intelligent therapeutic agents that have the ability for personalized and predictive medical intervention^{22,34}.

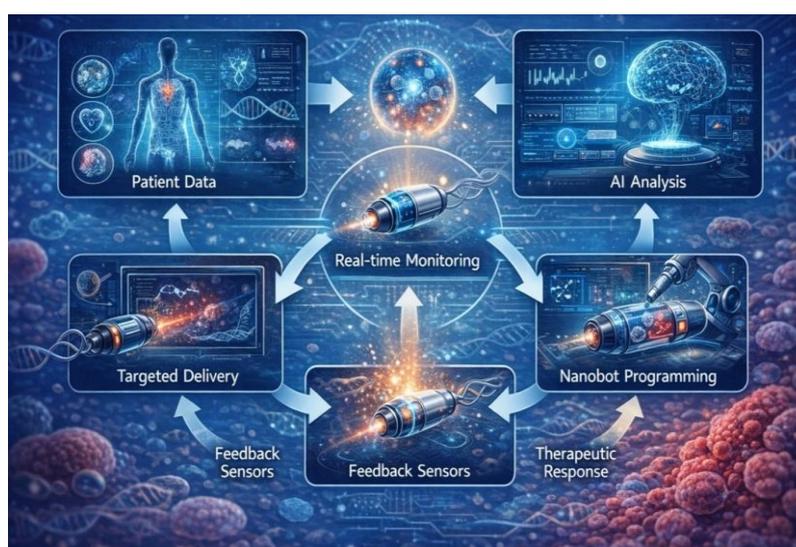


Fig.6:Flow Chart Of AI-Integrated Nanobot-Assisted Precision Medicine Workflow



Nanobots In Regenerative And Gene Therapy

Nanobots find a prominent place in regenerative medicine by facilitating guided stem cell migration, modifying tissue microenvironments, and directing tissue regeneration^{26,34}. In gene therapy, nanobots aid in the precise intracellular delivery of CRISPR/Cas systems and regulatory proteins for increasing efficiency as well as safety with respect to gene therapy^{13,26}. New advanced nanobot technologies include biodegradable materials and features of self-destruction to reduce accumulation and immunologic reactions, enhancing their biosafety profiles^{28,31}.

Regulatory, Ethical, And Manufacturing

The transition of pharmaceutical nanobots to the human body has faced challenges with respect to regulation, ethics, and production^{28,29}. Long-term biosafety, immune response, biodistribution, and toxicity are some challenges to be addressed for the uptake of nanobots^{2,3}. The European Medicines Agency and the United States Food and Drug Administration have issued guidance documents on the handling of nanotechnology-based medicinal products that highlight the need for standardized characterization, safety testing, and quality control^{31,32}. The development of nanobot-based therapeutics requires an interdisciplinary collaboration between pharmaceutical scientists, clinicians, engineers, and regulatory authorities with an objective to bridge the gap from innovation to clinical applicability.

Conclusion

The idea behind using nanorobotics in medicine came from early works that suggested we could manipulate matter at the nanoscale for health-related uses. Over the years, progress in nanotechnology, materials science, and pharmaceutical engineering has turned this idea into practical platforms. These platforms can control drug delivery, sensing, microsurgery, and detoxification. The combination of nanocarrier principles with robotic technology has further widened their use, especially in cancer treatment and managing chronic diseases. Unlike traditional nanocarriers, nanobots have active propulsion systems. This allows them to move on their own or to be guided externally within biological systems. Techniques like magnetic guidance, enzymatic propulsion, ultrasound-driven movement, and chemically powered nanomotors have shown they can navigate through blood vessels and complex tissue structures. This active movement addresses one major limit of passive nanoparticle delivery, which is poor penetration into tumors and uneven drug spread. By moving through abnormal tumor blood vessels and getting into dense extracellular spaces, nanobots improve drug concentration at specific sites and increase treatment effectiveness. Additionally, the shape of the particles, surface design, and biomimetic coatings greatly affect how long they stay in circulation and how they behave in blood vessels.

The development of programmable nanobots using DNA origami and logic-gated systems marks a major advance in precision targeting. These nanostructures can identify specific molecular markers and release therapeutic agents only when they meet certain pathological signatures. This improves specificity and reduces systemic toxicity. Additionally, stimuli-responsive nanobots are designed to react to changes in pH, enzymatic activity, redox gradients, or temperature. This allows for better control over drug release. Such microenvironment-triggered activation is especially useful in cancer treatment. Tumor tissues often have acidic and enzyme-rich conditions that differ from healthy tissues. Adding theranostic capabilities takes nanobots from being simple delivery devices to multifunctional biomedical systems. By including imaging agents, biosensors, or signal-emitting components, nanobots can diagnose diseases, track treatment responses, and adjust drug release accordingly. This dual function supports the goals of precision nanomedicine, which focuses on personalized treatments based on real-time biological data. The shift from theoretical nanomedicine to actual clinical use highlights the growing sophistication of the field.

Artificial intelligence (AI) plays a vital role in the development of next-generation nanobot systems. By analyzing genomic, proteomic, metabolomic, and imaging datasets, AI algorithms can pinpoint disease signatures specific to each patient and improve nanobot design parameters. Machine learning models help predict how substances will distribute in the body, assess toxicity, and estimate treatment outcomes, which speeds up the development of rational formulations. AI-driven precision nanomedicine also aids in planning treatments, especially in cancer care, where the diversity of tumors requires personalized approaches. Moreover, combining nanobots with gene therapy methods offers new opportunities for targeted genetic changes and repairs within cells. Despite these advancements, several challenges remain in translating this technology into practice. Assessing the safety of nanomaterials needs thorough evaluations of their immunogenicity, distribution in the body, long-term toxicity, and effects on the environment. Regulatory agencies have stressed the importance of standardized methods for characterizing nanomaterials and strong preclinical validation processes. Additionally, issues like large-scale manufacturing, reliability, cost-efficiency, and ethical concerns regarding autonomous medical devices create obstacles to widespread use in clinical settings.

Overcoming these challenges requires strong teamwork among pharmaceutical scientists, clinicians, nanotechnologists, AI



researchers, and regulatory authorities. Ongoing innovation in nanomanufacturing, safety profiling, and regulatory alignment will be crucial to ensure safe progress from laboratory research to clinical use. In conclusion, nanobots represent a significant advancement in pharmaceutical sciences. They combine nanotechnology, biotechnology, and artificial intelligence to create smart, adaptable, and less invasive treatment systems. As we address scientific and regulatory challenges, AI-assisted nanobots can change precision medicine. They will provide accurate diagnosis, targeted therapy, ongoing disease monitoring, and personalized treatment strategies that represent the future of smart therapeutics.

REFERENCES

1. Freitas RA. Nanomedicine, Volume I: Basic Capabilities. Georgetown (TX): Landes Bioscience; 1999.
2. Feynman RP. There's plenty of room at the bottom. *Eng Sci.* 1960;23(5):22–36.
3. Li J, Esteban-Fernández de Ávila B, Gao W, Zhang L, Wang J. Micro/nanorobots for biomedicine: delivery, surgery, sensing, and detoxification. *Sci Robot.* 2017;2(4):eaam6431.
4. Peer D, Karp JM, Hong S, Farokhzad OC, Margalit R, Langer R. Nanocarriers as an emerging platform for cancer therapy. *Nat Nanotechnol.* 2007;2(12):751–760.
5. Chen Y, Gao W, Li J, Wang J. Intelligent nanorobots in biomedical applications. *Adv Drug Deliv Rev.* 2022;180:114037.
6. Wang J. Nanomachines: Fundamentals and Applications. Weinheim: Wiley-VCH; 2013.
7. Gao W, Wang J. The environmental impact of micro/nanomachines: a review. *ACS Nano.* 2014;8(4):3170–3180.
8. Esteban-Fernández de Ávila B, Angsantikul P, Li J, et al. Micromotors go in vivo: from test tubes to live animals. *Adv Funct Mater.* 2018;28(25):1705640.
9. Soto F, Wang J. The vision of smart nanobots in medicine. *Nat Nanotechnol.* 2019;14(4):319–320.
10. Chen XZ, Hoop M, Mushtaq F, et al. Magnetically driven microrobots for targeted drug delivery. *Adv Mater.* 2017;29(14):1605458.
11. Sitti M, Ceylan H, Hu W, et al. Biomedical applications of untethered mobile milli/microrobots. *Proc IEEE.* 2015;103(2):205–224.
12. Li S, Jiang Q, Liu S, et al. DNA origami for drug delivery and therapeutics. *Nat Rev Mater.* 2021;6:361–376.
13. Douglas SM, Bachelet I, Church GM. A logic-gated nanorobot for targeted transport of molecular payloads. *Science.* 2012;335(6070):831–834.
14. Zhang Q, Jiang Q, Li N, et al. DNA origami as an in vivo drug delivery vehicle. *ACS Nano.* 2014;8(7):6633–6643.
15. Mitragotri S, Burke PA, Langer R. Overcoming the challenges in administering biopharmaceuticals: formulation and delivery strategies. *Nat Rev Drug Discov.* 2014;13(9):655–672.
16. Decuzzi P, Pasqualini R, Arap W, Ferrari M. Intravascular delivery of particulate systems: does geometry really matter? *Pharm Res.* 2009;26(1):235–243.
17. Wilhelm S, Tavares AJ, Dai Q, et al. Analysis of nanoparticle delivery to tumours. *Nat Rev Mater.* 2016;1:16014.
18. Peer D, Koren E, et al. Precision nanomedicine. *Nat Nanotechnol.* 2020;15:724–726.
19. Wang H, Moo JGS, Pumera M. From nanomotors to micromotors: the evolution of enzyme-powered autonomous machines. *Chem Rev.* 2015;115(16):8704–8735.
20. Xu T, Soto F, Gao W, et al. Ultrasound-propelled nanomotors for drug delivery. *ACS Nano.* 2015;9(2):1782–1789.
21. Kim K, Kim J, Lee JH. Artificial intelligence in nanomedicine. *Adv Drug Deliv Rev.* 2022;181:114101.
22. Topol EJ. High-performance medicine: the convergence of human and artificial intelligence. *Nat Med.* 2019;25(1):44–56.
23. Chen Y, et al. Theranostic nanomedicine. *Adv Drug Deliv Rev.* 2021;169:1–25.
24. Mura S, Nicolas J, Couvreur P. Stimuli-responsive nanocarriers for drug delivery. *Nat Mater.* 2013;12(11):991–1003.
25. Blanco E, Shen H, Ferrari M. Principles of nanoparticle design for overcoming biological barriers. *Nat Biotechnol.* 2015;33(9):941–951.
26. Gupta R, Rai B. Nanobots and gene therapy: prospects and challenges. *Drug Discov Today.* 2021;26(4):1081–1091.
27. Couvreur P, Vauthier C. Nanomedicine: from concept to clinical reality. *Adv Drug Deliv Rev.* 2006;58(14):1418–1432.
28. Fadeel B, Farcas L, Hardy B, et al. Advanced tools for the safety assessment of nanomaterials. *Nat Nanotechnol.* 2018;13(7):537–543.
29. Etheridge ML, Campbell SA, Erdman AG, Haynes CL, Wolf SM, McCullough J. The big picture on nanomedicine: the state of investigational and approved nanomedicine products. *Nanomedicine.* 2013;9(1):1–14.
30. Ventola CL. Progress in nanomedicine: approved and investigational nanodrugs. *P T.* 2017;42(12):742–755.
31. European Medicines Agency. Reflection paper on nanotechnology-based medicinal products. London: EMA; 2019.
32. U.S. Food and Drug Administration. Drug products, including biological products, that contain nanomaterials: guidance for industry. Silver Spring (MD): FDA; 2022.
33. Bhushan B. Nanorobotics and Nanomanufacturing. Cham: Springer; 2017.
34. Shamay Y, Shah J, Isik M, et al. Precision nanomedicine for personalized cancer therapy. *Nat Rev Clin Oncol.* 2018;15:449–464.



How to cite this article:

Prathyusha Vuddanda Ijppr.Human, 2026; Vol. 32 (3): 312-325.

Conflict of Interest Statement: All authors have nothing else to disclose.

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.